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Can geoeffectiveness of CMEs be predicted?

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Abstract. Coronal mass ejections or CMEs are well known as the drivers of enhanced interplanetary and geomagnetic activity. They are large expulsions of material from the Sun, which travel into the interplanetary (IP) medium and, if directed towards the earth, can reach the earth in 3-5 days. It is therefore, necessary to track a CME from the solar surface through the IP medium till it reaches the earth. Recent observations from different instruments aboard SOHO, which simultaneously image the solar atmosphere in different layers up to a distance of 32 $R_{\odot}$, have enabled us to study the initiation and the propagation of CMEs outward in the heliosphere. These observations reveal that the halo CMEs are the potential sources of geomagnetic activity at the earth. However, not all halo CMEs give rise to the geoeffective IP shocks, which adds to the problem of space weather forecasting. Here I propose to examine the characteristics of the geoeffective CMEs observed by LASCO/SOHO and discuss their role in the prediction of intense geomagnetic storms.

Keywords : CME–Halos–Ejecta–Geomagnetic storms

1. Present understanding of the problem

It is now quite well established that the CMEs play a key role in the solar-terrestrial relationship (Gosling 1993, Webb 1995). In particular, halo CMEs are considered as the potential sources of geomagnetic activity as they are directed towards the earth. A halo CME is a mass ejection in which the material is seen as expanding circular brightening all around the occulter and was first observed by Howard *et al.* (1982). Figure 1 shows a distinct example of a large halo CME observed by LASCO coronagraph on SOHO. The SOHO observations in extreme ultaviolet (195 Å) revealed an interesting phenomenon for the first time, viz., the travelling disturbances known as EIT waves, which were found to be associated with the halo CMEs(Thompson *et al.* 1998)(Figure 2). Thompson *et*

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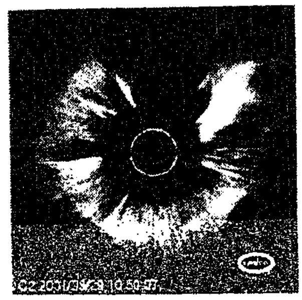

Figure 1. A full halo CME recorded on March 29, 2001, by LASCO-C2 coronagraph. The field of view of LASCO-C2 is 2-6 $R_\odot$.

al. (2000) showed that the EIT waves are travelling disturbances and are the coronal counterparts of the chromospheric Moreton waves (Smith and Harvey, 1971). These are commonly observed in association with halo CMEs. Their average speeds have been found to lie in the range of 200-300 km s^{-1}. Thus, EIT waves and halo CMEs are important signatures of earthward directed CMEs. The location of origin of halo CMEs is crucial for their impact on the earth. All front-side halos might be geoeffective provided they arise from favourable locations, i.e. if they originate close to the central meridian and at low-latitudes (Gonzalez *et al.* 1996; Srivastava *et al.* 1997, 1998 and Srivastava and Venkatakrishnan, 2002). However, the back-side halos also may occur, although they may not be strongly geoeffective. They take a longer time to arrive than the front-side ones. Figure 3 shows a high correlation between halos and geomagnetic storms. Out of 14 halos observed during 1996-1997, 12 resulted in geomagnetic storms. It is interesting to note that 6 out of 7 front-side halos (shown with solid vertical lines) resulted in geomagnetic storms, while one missed the earth. Further, 3 out of 4 halos which occurred back-side (marked by dashed vertical lines) also resulted in geomagnetic storms. However, there were at least 3 storms which occurred without halo-CME forewarning (Webb *et al.* 2000). From another recent analysis of observations taken during the period 1997-2001, we found about 66% of the observed geomagnetic storms were associated with full front-side halos,

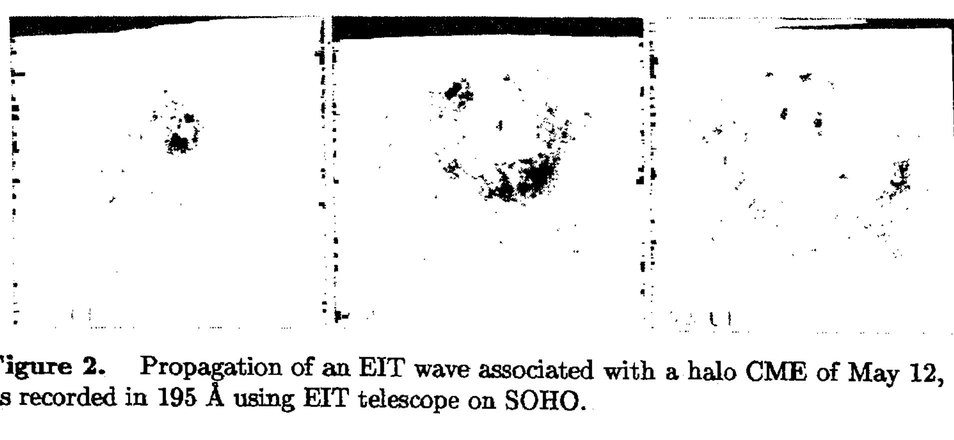

Figure 2. Propagation of an EIT wave associated with a halo CME of May 12, 1997 as recorded in 195 Å using EIT telescope on SOHO.

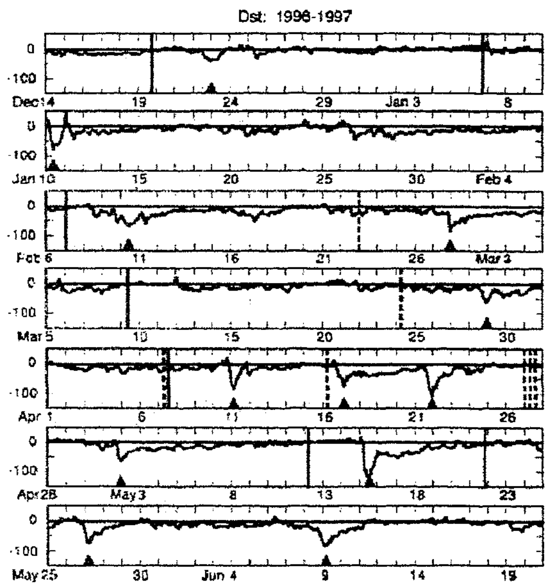

Figure 3. Geomagnetic activity association with solar surface activity during 1996-1997. Here, the solid and dashed vertical lines mark the occurrence of front and back-side halos respectively. The resulting geomagnetic storms are marked by solid triangles)(Adapted from Webb *et al.* 2000).

28% with partial halos with angular extent > 180° and 6% with none of these. The latter indicates that in rare cases, the limb events could also be geo-effective (Srivastava 2002). The key problem that poses challenge to the Space Weather physicists, is that one does not yet have a unique handle on what determines the geoeffectiveness. The studies made in the past have shown that the geoeffectiveness of the CMEs is mainly due to the increase in the solar wind speeds and the southward turn of the embedded magnetic field (Burton *et al.* 1975). In principle, we cannot measure the propagation speeds of the halo CMEs towards the earth as an observer at the earth is in a very unfavourable location for measuring the radial speed of such halos. Therefore, we look for proxy data which allows inference of the probable travel time towards the earth. Observations of CMEs in all directions show similar characteristics. One such characteristic is the geometrical shape of the ejected clouds which is maintained throughout the field of view of the LASCO coronagraphs on SOHO (1-32 $R_\odot$)(Brueckner *et al.* 1995). Thus, the radial propagation is closely related with the lateral expansion of the clouds. If only the lateral expansion speed is measurable (as is the case for halo events), the radial speed can be inferred. From LASCO data, we estimate the propagation speeds upto 32 $R_\odot$. Beyond this distance, near-earth ***in-situ*** measurements are being used for determining the speeds of the interplanetary ejecta. However, the lack of observations in the regime between the near-sun and near-earth leads to poor prediction of the space weather.

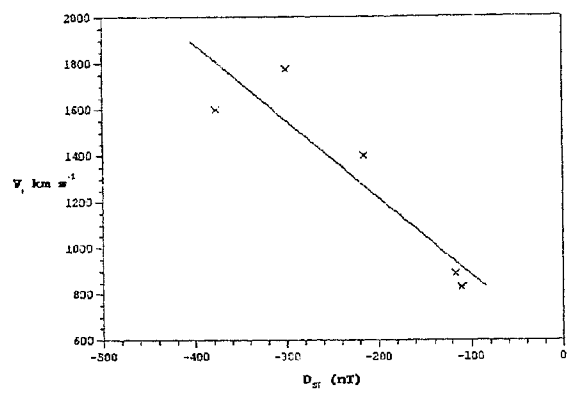

Figure 4. Dependence of the strength of the geomagnetic storm on the initial speeds of the halos.

In a recent study, the initial speeds of 5 halo CMEs observed by LASCO/SOHO during 1997-2001 were measured. These halos were associated with X-class flares (Srivastava and Venkatakrishnan, 2002). A comparative study of these events shows that the strongest storm ($D_{ST} \sim$ -377 nT) of the current solar cycle which occurred on March 31, 2001 had its source in very large sunspots which were approximately 8 times the average size of the sunspots of other active regions. The flare intensity in optical or x-rays did not indicate the strength of the resulting geomagnetic activity, as the flare associated with the CME of March 29, 2001 was 1F class. However, measurement of speeds of the halo CMEs showed that the initial speed of the CMEs is well correlated with the D_{ST} strength of the related storm (Figure 4). The ram pressure was calculated at L1 location, for each of the geo-effective events and it was found that there is a good correlation between the D_{ST} index and the ram pressure value. This study therefore, shows that the initial speed of the halos is a good predictor for the increase in the ram pressure of the resulting interplanetary shock and subsequently the severity of the geomagnetic disturbance due to its impact with the earth's magnetosphere. It should be noted that the measurements were based on the assumption that the radial speed is the same as the expansion speeds. However, recent analysis of several limb CMEs by Schwenn (2001) shows that the radial speed v_{rad} can be inferred from the expansion speed v_{exp} using the relation $v_{rad} = 0.88$ v_{exp} . For halo CMEs, v_{exp} can be determined easily and thus v_{rad} can be inferred.

2. Constraints for efficient prediction: a few exceptions

Study of LASCO observations shows low rate of geomagnetic storms as compared to the number of halo CMEs recorded. This happens because the ejecta associated with about half of the front-side halo CMEs which do not have their origin at a favourable location donot reach the earth. However, even when the associated source lies near central

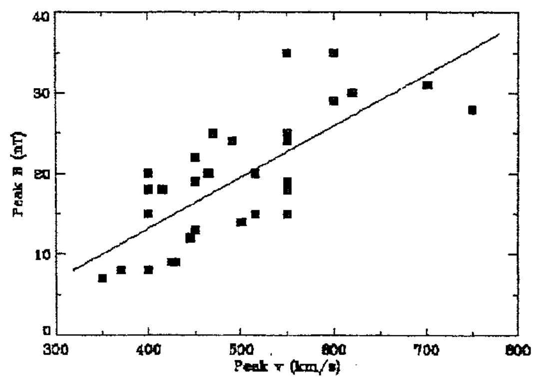

Figure 5. Relation between the peak values of the total magnetic field intensiy and the solar wind speed for the magnetic clouds. (Adapted from Gonzalez *et al.* 1998)

meridian an ejecta may not encounter the earth. The role of the southward magnetic field component embedded in the ejecta may be crucial. This implies that the ejecta arrival time and hence storm onset, must take into account the solar wind and interplanetary magnetic field conditions. A study of the relationship of the magnetic field of the cloud and the solar wind speed shows that the faster the cloud moves, the higher the core of the magnetic field as seen in Figure 5. Although compression of the cloud may be accounted for this relation, yet it is not well established. The travel time is an essential parameter to be predicted in Space Weather study. This is defined as the time difference between the first appearance of a CME in EIT/LASCO instruments and the arrival of the shock and its interaction with the earth's magnetosphere. It was found that the travel time for most of the CMEs is 80 hours. Only for exceptionally fast CMEs (exceeding a speed of 1000 km s^{-1}) the travel time is of the order of 50 hours (Srivastava 2001).

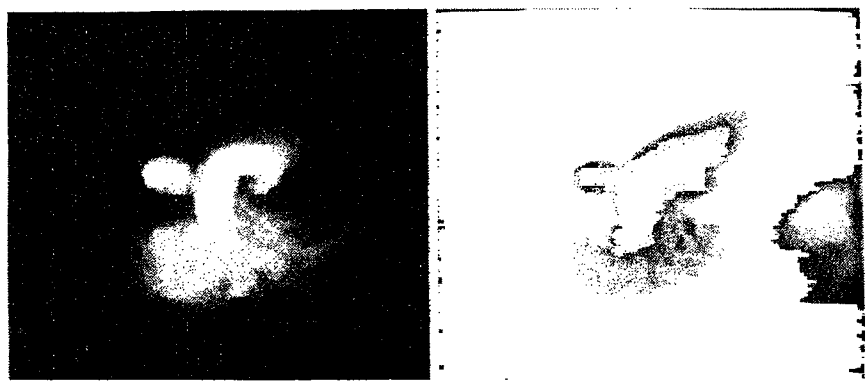

Figure 6. "S" shaped structure as the sigmoid prior to a CME (left panel). The right panel shows the cusp shaped structure after the CME has taken off.

Once the timings of the launch of the CME is known, the uncertainty in the prediction of the arrival time of CMEs at the earth is of the order of a few hours, in fact the real challenge for solar physicists lies in the prediction of the events before they occur. Efforts are under way to answer this crucial question. Recent results of Canfield *et al.* (1999) shows that "S-shaped" soft x-ray structures or sigmoids seen in YOHKOH images are potential source-sites of CME (Figure 6). These structures are a measure of helicity of the solar magnetic field of the CME and are directly linked to the chirality of the solar hemisphere from which they originate (Rust 1994). More work needs to be done on sigmoid structure to use them as a prediction tool particularly from their relation with non-potentiality of the vector magnetic field.

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